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Observation of Flow and Temperature Oscillations Around a Bubble on a Solid Surface Subject to a Vertical Temperature Gradient

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OBSERVATION OF FLOW AND TEMPERATURE OSCILLATIONS AROUND A BUBBLE ON A SOLID SURFACE SUBJECT TO A VERTICAL TEMPERATURE GRADIENT

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Abstract

In space and many industrial cases on earth which involve materials processing, manufacturing, and storage and management of liquids, the interaction between gas and vapor bubbles with the surrounding is of great interest. Study of thermocapillary motions near bubbles attached to a heated or cooled wall in conjunction with the space experiments has received considerable attention in recent years. We present results of preliminary experimental observations which have indicated that when the Marangoni number is increased beyond a critical value, a series of oscillatory modes develop in the vicinity of the bubble. The oscillations have been detected in both the basic flow induced by combined Marangoni and buoyancy effects, by using a laser sheet for tracing particles, and in the temperature field visualized by interferometry techniques. The influence of the Marangoni and Prandtl numbers and bubble geometry on the oscillations are indicated.

Introduction

A comprehensive review paper by Ostrach[1] drew attention to the importance of Marangoni convection in materials processing and fluid management in space. Interaction of gas and vapor bubbles with surrounding fluid is of great interest. Because of the pronounced effects of capillary forces in reduced gravity environment, it can play a significant role in materials processing, fluid management and boiling processes in space. On earth this interaction is manifested by a fluid motion brought about by two coexisting and sometimes competing mechanisms; natural convection induced by the volumetric buoyancy force and Marangoni convection driven by the interfacial stresses along the bubble surface. On earth, the volume forces are dominant in systems with large volume to surface ratio, but in microgravity conditions of orbiting spacecraft, the surface forces become more important. Nonetheless, understanding the intricacies of the Marangoni convection is not only essential for space processing but may also be extremely beneficial in controlling ground-based experiments and interpreting their results. As a result, there has been numerous work reported in the literature investigating the role of thermocapillary flows in the past decade. In general, these papers can be classified into two categories.

The first category consists of studies dealing with bubble/droplet migration caused by Marangoni convection. Young et al.[2] (1959) were the first to analyze thermocapillary migration of bubbles/droplets. They calculated the terminal velocity of a migrating droplet placed in an infinite fluid, with a linear temperature distribution far away from the droplet. They also performed an experiment observing bubbles in a liquid bridge formed by the gap between the anvils of a micrometer. They heated the lower anvil, so that the thermocapillary force was opposing the force of buoyancy, and adjusted the temperature gradient so that the bubble was stationary. This temperature gradient was measured for different bubble sizes and compared with theory. A good agreement with theory was reported within the limits of their experimental accuracy. Other major research efforts focused on thermocapillary migration of bub-

*Senior Scientist, NYMA, Inc., Senior Member AIAA bles and drops is due to Subramanian and coworkers at Clarkson University[3,4], Microgravity Fluids group at NASA Lewis Research Center[5,6]. These research teams have performed combined activities of theoretical and experimental studies of thermocapillary bubble/drop migration in reduced gravity environments.

The second category which has received much less attention includes bubble dynamics attached to heated/cooled surface and interaction with the fluid surrounding it. The need for major research in the area of the interaction of bubbles with solidification interfaces in low gravity environment was demonstrated by Papazian and Wilcox[7]. Larkin[8] conducted a numerical study of the Marangoni effect around a hemispherical bubble placed on a solid wall. The initial condition is an isothermal field, then the wall is heated with a constant heat flux. The author obtained time-dependent numerical solutions for the flow for Marangoni numbers between 0 and 100,000 and Prandtl numbers 1 and 5. He found the flow built up quickly then gradually declined with time but he was unable to continue the solution until steady-state was reached nor was he able to predict an oscillatory flow because of enormous amount of computer time required. Kao and Kenning[9] extended the work of Larkin[8] by taking into account heat transfer at the interface between the gas and the liquid and studied the effect of surfactant on the flows. They covered a range of Marangoni numbers from 50 to 250,000 and Biot numbers from 0 to 5000. They did not detect flow oscillations either.

These results contradict recent observations by Raake et al.[10] and Chun et al.[11] who have experimentally visualized thermal oscillations, at Marangoni numbers above 12,000 and 6830 respectively, using Schlieren interferometry. These are in accordance with unsteady thermocapillary flows induced at higher Marangoni numbers in liquid bridges or free surface cavities. In this category one can mention thermocapillary oscillatory flows in liquid bridges that have been studied experimentally by Chun[12]; Kamotani et al.[13]; theoretically by Kuhlmann and Rath[14], and most recently time-dependent thermocapillary studies in a shallow Cartesian cavity for a Prandtl number 6.78 fluid has been conducted by Peltier and Biringen[15]. In their numerical experiment Peltier and Biringen predicted oscillatory flows near a critical Marangoni number of 20,000 for a Prandtl number of about 7.0. In contrast to the fairly extensive studies of thermocapillary flows, our understanding of thermocapillary bubble dynamics on heated/cooled surfaces remains primitive. Largely to enhance our understanding and to resolve some of the above inconsistencies we have conducted a preliminary investigation of temperature and flow in the vicinity of a bubble attached to a heated surface. The results which will be discussed below clearly indicate the initiation of periodic oscillation at Marangoni numbers comparable to other research results in the field, although different in problem configuration, such as findings of Peltier and Biringen[15].

Another objective of the present experimental work is to develop an experimental methodology to enable investigation of the fluid flow and temperature fields in the vicinity of the bubble attached to a heated solid surface as a guidance for future numerical modelling and design of an experiment for low gravity environment which will be postponed to a future paper. The prime concern of this paper is to identify experimentally and demonstrate steady state, transition to and initiation of the unsteady, and periodic oscillation of the flow and temperature fields surrounding a bubble on a heated surface. To this end, we have attempted to identify some parametric range for which transition to unsteady periodic and non-periodic oscillations are initiated. The fluid flow is governed by an intricate interaction between the buoyancy driven natural convection and the thermocapillary driven Marangoni convection. The interaction between these driving forces and their effect on the transition to unsteady flow can be very different in microgravity conditions. While the results of such studies may not deal specifically with either fluid handling, boiling and materials processing or application areas, the knowledge generated by our research will have direct impact on all. This report will only consider one-g condition in the hope that these observations may be used as a precursor and a comparison base for future microgravity experiments.

Parametric Definitions and Physical Considerations

Marangoni convection is the result of local surface/interfacial tension gradient, such as shown in Fig. 1. One can show that the balance of forces at the interface in a steady state thermal Marangoni (thermocapillary) convection case as:

$$\mu_2 \left(\frac{\partial (u_s)_2}{\partial n} + \frac{\partial (u_n)_2}{\partial s} \right)$$

$$-\quad \mu_1\left(\frac{\partial(u_s)_1}{\partial n}+\frac{\partial(u_n)_1}{\partial s}\right)=\frac{d\sigma}{ds}, \qquad (1)$$

$$\begin{aligned} p_2-p_1+\sigma\left(\frac{1}{R_2}+\frac{1}{R_1}\right) \\ = \; 2\left(\mu_2\frac{\partial(u_n)_2}{\partial n}-\mu_1\frac{\partial(u_n)_1}{\partial n}\right). \end{aligned} \qquad (2)$$

If one also assumes that the flow is parallel to the interface as shown in Fig. 1, equations 1 and 2 can be reduced to

$$\mu_2\frac{\partial(u_n)_2}{\partial n}-\mu_1\frac{\partial(u_n)_1}{\partial n}=\frac{d\sigma}{ds}, \qquad (3)$$

$$p_2-p_1+\sigma\left(\frac{1}{R_2}+\frac{1}{R_1}\right)=0. \qquad (4)$$

It is well known that surface tension is dependent on the temperature (T), concentration (C), and electric potential (E_p), i.e., $\sigma=\sigma(T,C,E_p)$, and if gradients exist in any such variables, there will be a corresponding gradient in the interfacial tension, causing a tangential force in the interface that is accompanied by fluid flow of interface and the bulk of the fluids. In some cases, this flow may be quite vigorous and time-dependent, and perhaps even turbulent, causing significant convection in the bulk fluids. There are many cases in which the three are strictly analogous, especially when they act in the absence of others and when the interfacial structure is simple from a molecular viewpoint. Note that we deal only with thermocapillary convection in this paper, although this work can be relevant to these other phenomena as well.

From the following expression[1];

$$\begin{aligned} \frac{d\sigma}{ds} \;=\; & \left(\frac{\partial\sigma}{\partial T}\right)\left(\frac{\partial T}{\partial s}\right)+\left(\frac{\partial\sigma}{\partial C}\right)\left(\frac{\partial C}{\partial s}\right) \\ + \; & \left(\frac{\partial\sigma}{\partial E_p}\right)\left(\frac{\partial E_p}{\partial s}\right) \end{aligned} \qquad (5)$$

and according to the above assumption, equation (5) may be reduced to $\frac{d\sigma}{ds}=\sigma_T(\frac{\partial T}{\partial s})$, where $\sigma_T=\frac{\partial\sigma}{\partial T}$, in general, is a negative constant for most Newtonian fluids. In the case of thermocapillary convection near a gas bubble on a heated surface (in a stably stratified fluid on earth) as shown in Fig. 2, the following assumptions are reasonable to be considered:

$$\mu_G \ll \mu_L, \quad \alpha_G \ll \alpha_L, \quad \text{and} \quad \rho_G \ll \rho_L \qquad (6)$$

where subscripts G and L represent gas and liquid phases respectively. It is, therefore, possible to describe the present problem by a group of governing dimensionless parameters of the bulk liquid phase, and avoid using these subscripts hereafter. Analysis and nondimensionalization of the continuity, momentum and energy equations show that the important parameter groups for this problem are: Marangoni number $Ma = RePr = (\rho\frac{lu_m}{\mu})(\frac{\nu}{\alpha})$, where Re is a Reynolds number, Pr is Prandtl number, ρ is the mass density of the bulk fluid, u_m is a characteristic velocity defined as $|\frac{\partial\sigma}{\partial T}||\frac{\partial T}{\partial z}|(\frac{z_B}{\mu})$, length z_B can be chosen for this velocity scale because the ranges of velocities observed in the primary vortex surrounding the bubble, (see Fig. 2), for $Re < 1$, has the same order of magnitude as the normal distance of the interface to the center of this vortex. Also l is a characteristic length scale, μ and ν are dynamic and kinematic viscosities respectively, and α is the thermal diffusion coefficient of the test fluid. The Prandtl number is a function of temperature due to the dependence of the kinematic viscosity ν, and the thermal diffusion coefficient α on temperature. In our experiment the Pr ranges has been estimated to be between 5 to 28 for the temperature ranges used. The dynamic Bond number, Bo, can be defined as the ratio of Rayleigh number to Marangoni number; $Bo = Ra/Ma = g\beta l^4\frac{|\frac{\partial T}{\partial r}|}{(\nu\alpha Ma)}$, where g is the gravitational acceleration, β is the coefficient of thermal expansion, $l = r_B$ is a characteristic length, and $\frac{\partial T}{\partial r}$ is the horizontal temperature gradient. We note that $\frac{\partial T}{\partial r}$, as a characteristic gradient near the bubble, is inherently coupled with $\frac{\partial T}{\partial z}$, henceforth, Bo as a function of Ma is estimated to be 0.2 to 2.3 in the present experiment.

Since a significant temperature variation on the bubble surface mainly confined to a vicinity surrounding the bubble height, z_B is considered to be a characteristic length, and therefore, a bubble shape parameter can be defined as $A_r = \frac{r_B}{z_B}$. The pattern of the flow including the unsteady periodic and non-periodic flows show strong dependence on the horizontal extent of the bubble, r_B, a modified Ma is finally defined as $Ma_m = MaA_r$, and has been used in the present data analysis.

Liquids Properties

Table 1 shows the necessary thermophysical properties of the liquids used in this experimental project. Surface tension σ, and thermal surface tension coefficient, σ_T, were measured using a du Nuoy ring method. The thermal coefficient of refractive index has been calculated by a formula for liquids suggested by Vest[16] which has been used in obtaining the temperature distributions in the test cell. The rest of the properties are given in the DOW CORNING 200 fluids literature.

Experimental Apparatus

One of the primary tasks of this research project is to develop an experimental operational set up capable of demonstrating the thermocapillary flow in the proximity of a bubble attached to a solid wall and subject to a vertical temperature gradient. The steady state and onset of the oscillations have been determined by observation of the temperature and the flow field near the bubbles investigated using the following test cell. The schematic of the test cell which is made of optical quality *F*. silica windows suitable for interferometric measurements is shown in Fig. 3. The test enclosure has inside dimensions of 38mm × 19mm × 19mm (w × d × h). The transparent side walls are also suitable for laser light sheet illumination. The copper top and bottom walls are heated and cooled in order to establish the desired temperature gradients. Two small tanks are diagonally located in the corners of the upper copper wall and connected to the test cell via capillary holes. These will allow for expansion and/or contraction of the test liquid. These holes are also used to supply and remove the test liquid by controllable syringes. The center of top and bottom plates is equipped with thermocouple probes to control and observe the solid surface temperatures. The variations could be controlled within 0.1 degree celsius at any desired temperature used in the present experiment. There is a capillary opening with a connection to a syringe at the center of the top plate for bubble injection. Several concentric circles with minute sharp edges are formed around the injection hole to hold various size bubbles. After the chamber is filled with the test liquid and placed in the diagnostic system (consisting of an interferometer and the laser sheet flow visualization arrangement), the fluid is heated from above and cooled from below by two independently controlled thermostatic circulation baths connected to the copper plates. The temperature distribution in the cell can be accurately measured by the interferometer for up to 3 degree C per centimeter with resolution of 0.065 degree celsius per fringe. Beyond this temperature gradient, the temperature variation at the center line of the test liquid was measured by a 0.5 mm diameter stem K-type thermocouple probe (through the capillary hole of the top plate) capable of resolving 0.1 degree celsius. The motion and position of this thermocouple was controlled via a traverse mechanism. To ensure of two-dimensionality and steady state temperature and stably stratified condition prior to the injection of bubbles, interferograms of density distribution and motion of particles in the test cell from a series of recorded images, such as pictures shown in Fig. 5, were checked. Heat losses through the side walls and windows were negligible as confirmed from the flatness of fringes in interferograms near the walls. When a desired temperature difference in the test cell has reached to its steady state condition and checked as mentioned earlier, an air bubble of a fixed volume size was injected.

The flow fields were visualized with a low power 10 mW laser light sheet at the meridian plane of the bubble. Neutrally buoyant particles, added to the test liquid, were used as flow tracers. The movement of the tracer particles were recorded by a time-lapse recorder on S-VHS tapes for flow pattern and oscillation detection. The temperature fields were visualized by a Mach-Zehnder interferometer[17] (MZI). The entire diagnostic instrumentation and the test cell, except for the thermal controlling constant baths, were installed on a vibration-isolation optical table. The baths were connected to the test cell via flexible tygon tubing. Figure 4 shows the arrangement of the interferometer. Light rays traversing through a phase object furnish an integral information about the refractive index distribution of the medium they have travelled through. The interferograms can be analyzed to study the temperature (or density) fields and to detect instabilities around the bubbles. These interferograms and the laser sheet flow visualization images were continuously recorded and were analyzed later to obtain the frequency of periodic oscillations.

Discussion of Results

In this experimental study we have been able to demonstrate the basic thermocapillary flow near a bubble resting on a heated wall. Once the bubble is formed on the heated surface and the interface between air and the bulk fluid is formed, the thermocapillary convection begins immediately. This, in turn, disturbs the stable stratification near the bubble and a horizontal temperature gradient will form which results in a buoyancy force induced by the thermocapillary flow. The buoyancy force near the interface is counter-acting the thermocapillary induced flow force. Impression of the horizontal gradient can be deduced from the fringes near the bubble. It can also be observed from Fig. 6a, for basic steady flow, the fringes are packed beneath the bubble. This points to the fact that the temperature gradient is higher than the regions far away in horizontal distances from the bubble, indicating that an enhanced heat transport in the vertical direction beneath the bubble has occurred.

Shown in Fig. 6, is the steady state condition of index of refraction field and a photo of long time-exposure image of particle tracers near a bubble for the low Pr liquid at the temperature gradient of 3.2 degree celsius per centimeter. Figure 6b shows, although faintly, the primary vortex near the bubble, and weak flow field could be seen by the stationary particles far away from the bubble. Transition from basic steady state to an unsteady flow condition and onset of the oscillations for particular bubble size and at higher temperature gradients have been observed. Data samples of parameters obtained from the tests are given in Table 2. When a critical temperature gradient has been applied, the flow from its basic steady state makes a transition to an oscillatory mode which shows symmetric images of interferograms with respect to the vertical axis of the bubble. A typical symmetric oscillation field can be observed in Fig. 7. Similar instability phenomenon, at a much higher temperature gradient, has also been observed when a higher Prandtl number test fluid was used. Laser sheet particle flow visualization has also shown similar oscillations in the velocity distributions around the individual bubbles. At higher Marangoni numbers (around 78,000) the oscillations show asymmetric interferometric images as shown in Fig. 8. The asymmetry observed in the interferograms is an indication of other modes of oscillations as have been reported by Chun et al.[11]. By tracking a single particle around the bubble, modes of oscillation, observation and analysis of the modes, and phase velocity of azimuthal waves have been given by Chun et al.[11]. In their analysis, they have argued and used the primary vortex center normal distance from the bubble interface as the characteristic length. Chun et al. have used, then, the secondary vortex as a base to define various azimuthal travelling waves and describe associated modes of oscillations. In contrast, we have used the bubble radius which is the distance between the vertical axis of symmetry and a vertical line tangent to the bubble surface as the main characteristic length scale. This distance, at the bubble surface, near which high thermal gradients exists and the strong basic and oscillatory flow originates, remains rather fixed and unique for each individual bubble subject to investigation. For this reason we prefer to use this length, r_B, as the length scale in our non-dimensional parametric calculations. These results are given in Table 2. Extensive experiments with very fine steps of varying temperature gradient and bubble size along with efforts by numerical modelling studies are needed to quantify and fine tune the temperature and velocity fields around bubbles to accurately delineate the parametric space and to specify exact conditions for the onset of these oscillatory flows. These are currently being pursued and further discussion of our findings will be postponed for future reports. Here, however, we are only presenting our first attempt of analysis of a limited number of tests of the present experimental work in Table 2. For the fluid with low Pr the steady state (S.S.) and sometimes transition to unsteady flow were observed up to $Ma_m < 20,000$. In this range of Marangoni numbers, we are unable to assign a frequency of oscillation because the flow seems to be in transitional state and in non-periodic mode. The transient regimes were detected before the periodic oscillations were fully set in. At Ma_m larger than 20,000, clear transition to unsteady temperature near the bubble contact line to the heated surface were first detected from visualization of the interferogram images of index of refraction field surrounding the bubble. Once the flow became fully oscillatory at this condition, the frequency of these motions could be obtained either from the interferograms or from the particle tracer images (not given in this report) recorded on video tapes. The frequency of oscillations have a rather narrow band (about 0.215-0.272 Hz for low Pr test liquid, and 0.345-0.454 Hz for the second test liquid with higher Pr) for some range of temperature gradients and bubble sizes as given in Table 2. The period of these frequencies was obtained from the recorded video tapes by visually counting at least ten repeated patterns and calculated average time for one cycle. Around some Ma_m = 78,000, the flow exhibited clear asymmetric pattern as shown in a typical case shown in Fig. 8. This was followed by a non-periodic oscillation and chaotic flow patterns at estimated Marangoni numbers around 110,000. At these higher thermal gradient conditions when non-periodic flow regime takes place, the bubble behaves quite different from what observed at lower thermal gradients. The entire bubble showed a jerking motion around its position to sides and flow became even more chaotic because of this bubble motion. Neither surface deformation nor jerking of the bubble was detected in any of the previous lower temperature gradient cases. In the chaotic regime fringes in the interferometric images of the flow became very dense and difficult to recognize, and they will not be discussed any further in this paper. The symmetric and asymmetric oscillations observed by interferometry have been attributed to the azimuthal travelling modes of oscillations as have been pointed out by Chun et al.[11]. We are not presenting any three dimensional studies of the phenomena in this report until a proper method for detection of these azimuthal travelling structures is devised. Plans to this end are underway.

As a precaution and a side effort to ensure that at moderate thermal gradients (6 to 10 degree celsius per centimeter) the cause of the instabilities was not the effect of mere evaporation/condensation of fluid through the bubble surface, the following measures were taken. This was prompted based on oscillations observed by the author, in a mixture of methanol-water hanging droplet in silicone oil subject to both isothermal and non-isothermal test conditions[18]. A series of tests were run which details are not given here. Briefly, the top wall was held at temperatures below 21 degree celsius, while the thermal gradients in the test enclosure were controlled at comparable gradients as used in the tests with higher temperatures of the top wall cases. In these tests it was observed and concluded that the transition from basic steady to unsteady flow occurred at the same thermal gradients for similar size bubbles for both cases.

The flow induced a locally larger temperature gradient below the colder pole of the bubbles than in an undisturbed fluid. This, in turn, was associated with a lateral temperature gradient which caused a buoyancy force counteracting the thermocapillary flow force. The buoyancy force can not be neglected and may have an effect on the instability that is unknown as of yet. Periodic oscillatory temperature and flow fields were observed beyond some critical Marangoni numbers that agree with the results reported by Kamotani et al.[13], and Peltier and Biringen[15]. It is known that thermocapillary flow becomes oscillatory under certain conditions but its cause is not yet completely understood. The least understood part is the role free surface deformability plays in the oscillation mechanism. No obvious deformations on the bubble surface were observed except at very highest temperature gradient used in this experiment, which caused non-periodic and chaotic flow and jerking the bubble around. The higher the Pr, the higher the temperature gradient is required to drive the flow into the unsteady regime. In other words, for lower Pr liquid a much lower thermal gradient was necessary to initiate the oscillation in the flow surrounding the bubble. Evaporation/condensation for low ranges of thermal gradients did not seem to be the cause of the instabilities.

Conclusion and Future Plans

A preliminary experimental study has been conducted and used the Mach-Zehnder interferometry technique to observe and demonstrate the steady, periodic and non-periodic oscillatory temperature fields surrounding several individual air bubbles on a solid wall subjected to various temperature gradients. Simultaneous flow visualization by the interferometric technique and particle tracking in a laser-sheet have revealed interesting flow patterns and oscillations were detected surrounding individual air bubbles attached to the heated surface. A unique test cell for this feasibility experiment was designed and used to demonstrate the ability of the system to be used in thermocapillary bubble dynamic studies near a heated surface.

Observation of these instabilities by the limited tests, explained above, has prompted us to pursue rigorous tests and to identify exact range of parameters for various flow regimes observed in this first attempt of preliminary experimental study. As a future plan, further efforts will be focused on developing an improved, compact, and robust instrument, such as a local reference beam interferometer[19]. Analysis techniques for extraction of two-dimensional temperature distribution from an axisymmetric configuration such as the bubble dynamics problem at hand is needed and efforts in this regard are being pursued[20]. The low-gravity experiment would eventually enable the reduction of the effects of buoyancy and subsequently the mechanism responsible for these instabilities may be characterized. Plans to that effect are also being pursued[21].

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Table 1 - Properties of the Test Fluids

Property	Name	0.65 cSt. Silicone oil at 25°C	2.0 cSt. Silicone oil at 25°C	Dimensions
σ	Surface Tension	15.9	18.7	dynes/cm
$\frac{\partial\sigma}{\partial T}$	Temperature Coefficient of Surface Tension	-0.0991	-0.0743	dynes/cm°K
ρ	Density	0.7600	0.8700	g/cm^3
ν	Kinematic Viscosity	0.0065	0.0200	cm^2/sec
μ	Dynamic Viscosity	0.00494	0.0174	dynes sec/cm^2
Cp	Specific Heat	0.41000	0.4100	cal/g °K
κ	Thermal Conductivity	0.00024	0.00026	cal/cm °K sec
α	Thermal Diffusivity	0.0007702	0.00073	cm^2/sec
β	Coefficient of Expansion	0.0013400	0.00117	°K^{-1}
Pr	Prandtl Number	8.439	27	
$\frac{\partial n}{\partial T}$	Temperature Coefficient of Index of Refraction	-5.1413×10^{-4}	-4.679×10^{-4}	°K^{-1}

Table 2 - Preliminary Test Condition and Results

$\frac{\partial T}{\partial Z}$ [$°K/cm$]	Frequency [Hz]	r_B [mm]	$\frac{r_B}{Z_B}$	Ma	$Ma \cdot \frac{r_B}{Z_B}$	Flow Mode/ Regime
$Pr = 8.4$ Silicone Oil						
3.16	0.000	2.350	1.093	4,542	4,964	Steady State
3.16	-	4.500	1.607	16,656	26,766	Steady State/Tr.
6.32	0.000	1.933	1.000	5,943	5,943	Steady State
6.32	-	2.850	1.273	13,371	17,021	Transitional
6.32	0.259	3.250	1.413	17,387	24,568	Sym. Osc.
6.32	0.238	4.000	1.569	26,338	41,324	Sym. Osc.
6.32	0.215	5.125	1.970	43,236	85,175	Sym. Osc.
9.47	0.000	1.000	0.870	2,467	2,147	Steady State
9.47	-	1.625	0.985	6,516	6,418	Transitional
9.47	0.272	2.725	1.267	18,323	23,215	Sym. Osc.
9.47	0.252	3.525	1.469	30,661	45,040	Sym. Osc.
9.47	0.244	4.575	1.694	51,647	87,511	Asym. Osc.
22.00	-	3.150	2.100	56,857	119,400	Non-Per. Osc.
$Pr = 27$ Silicone Oil						
23.16	0.000	1.550	1.033	5,394	5,572	Steady State
23.16	0.454	2.750	1.279	16,980	21,718	Sym. Osc.
23.16	0.429	3.400	1.545	25,956	40,101	Sym. Osc.
23.16	0.345	4.750	1.900	41,194	78,269	Asym. Osc.

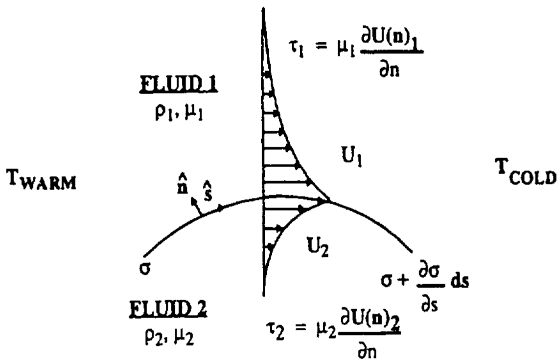


Figure 1 – Fluid/Fluid Interface with Temperature Gradient

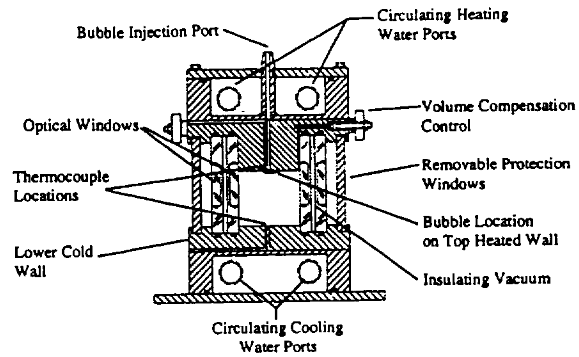


Figure 3 – Experiment Test Chamber (Not to Scale)

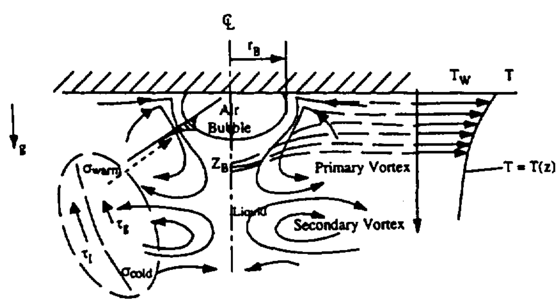


Figure 2 – Mechanismm of Thermocapillary Natural Convection Surrounding a Bubble on a Heated Wall

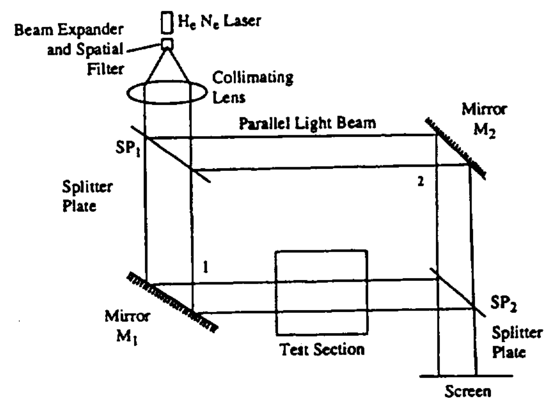


Figure 4 – Mach–Zehnder Interferometer

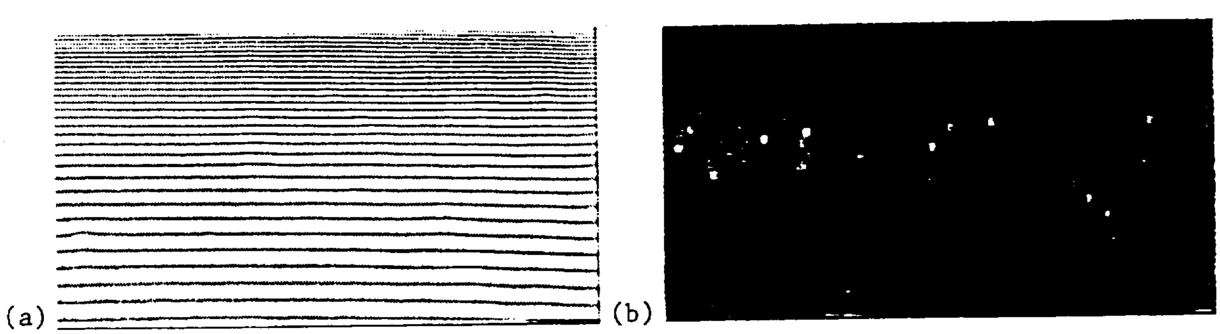
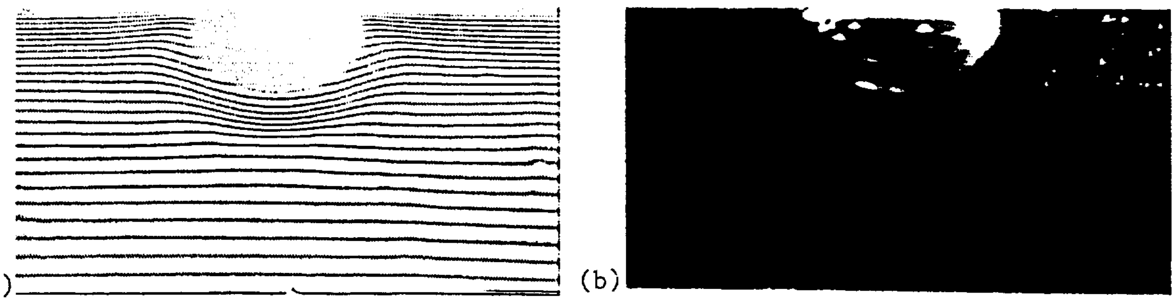


Figure 5 – Interferogram (a) of Temperature/Density Distribution and Long Time–Exposure Photo (b) of Stably Stratified Condition Before Bubble Injection



(a) (b)

Figure 6 – Inferferogram (a) Laser Sheet (b) Images of Steady State Temperature and Flow Surrounding the Bubble (d_B = 4.285 mm)

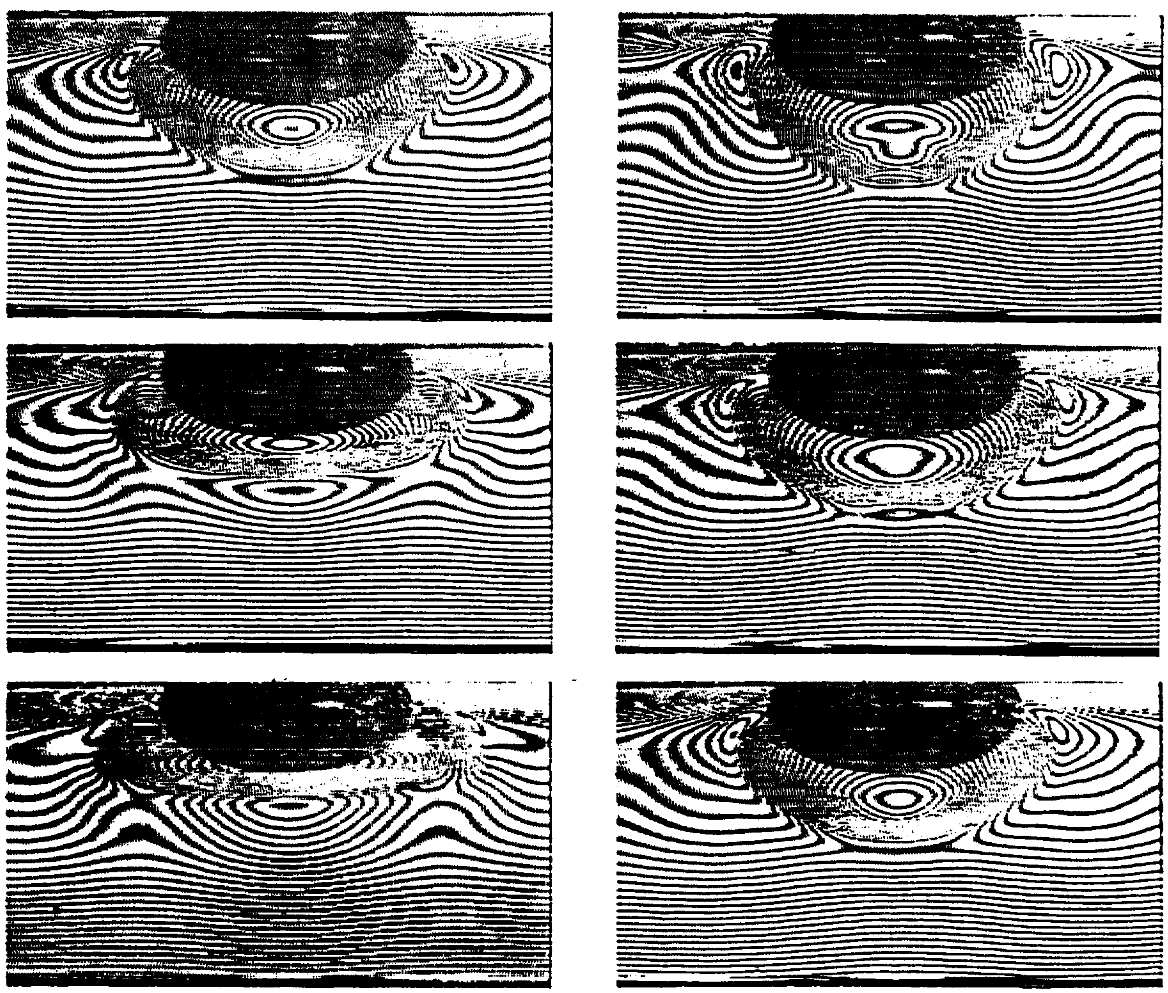


Figure 7 – Sequence of Interferograms for Symmetric Oscillatory Case of Refractive Index Field Near the Bubble (d_B = 6.285 mm)

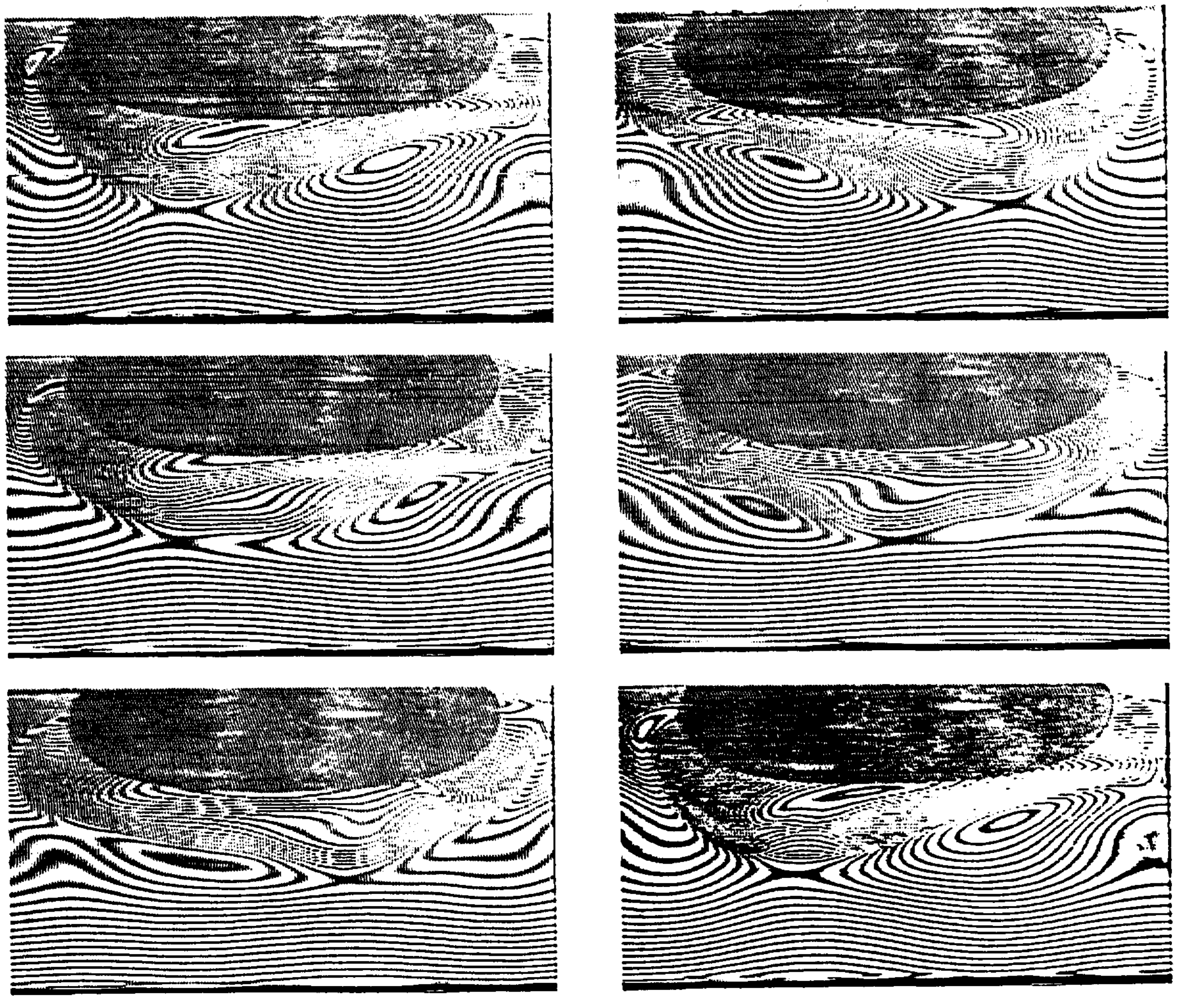


Figure 8 – Sequence of Interferograms for Asymmetric Oscillatory Case of Refractive Index Field Near the Bubble (d_B = 10.94 mm)

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13. ABSTRACT ***(Maximum 200 words)***

In space and many industrial cases on earth which involve materials processing, manufacturing, and storage and management of liquids, the interaction between gas and vapor bubbles with the surrounding is of great interest. Study of thermocapillary motions near bubbles attached to a heated or cooled wall in conjunction with the space experiments has received considerable attention in recent years. We present results of preliminary experimental observations which have indicated that when the Marangoni number is increased beyond a critical value, a series of oscillatory modes develop in the vicinity of the bubble. The oscillations have been detected in both the basic flow induced by combined Marangoni and buoyancy effects, by using a laser sheet for tracing particles, and in the temperature field visualized by interferometry techniques. The influence of the Marangoni and Prandtl numbers and bubble geometry on the oscillations are indicated.

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